MEASUREMENT OF THE SPECTRAL ABSORPTION OF LIQUID WATER IN MELTING SNOW WITH AN IMAGING SPECTROMETER

Robert O. Green[1,2] and Jeff Dozier[2]

[1]Jet propulsion Laboratory, California Institute of Technology, PasadenaCA91109
[2]University California, Santa Barbara, CA 93106

1. INTRODUCTION

Melting of the snowpack is a critical parameter driving aspects of the hydrology of regions of the Earth where snow accumulates seasonally. Measurement of snow melting over regional scales offers the potential to improve measurement, monitoring and modeling of snow driven hydrological processes. In this paper we present results showing the measurement of the spectral absorption duc to liquid water in a melting snowpack with the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS).

AVIRIS data were acquired over Mammoth Mountain, in east central California on 21 May 1994 at 18:35 UTC (Figure 1), The air temperature at 2926 m on Mammoth Mountain at site A was measured at 15 minute intervals during the day preceding the AVIRIS data acquisition. At this elevation, the air temperature did not drop below freezing the night of the May 20 and had risen to 6 degrees Celsius by the time of the overflight on May 21. These temperature conditions support the presence of melting snow at the surface as the AVIRIS data were acquired.

2. OPTICAL PROPERTIES OF LIQUID WATER ANI) ICE

The basis for the spectral measurement of liquid water is derived from the optical properties of liquid water in the 400 to 2500 run range. To spectrally measure liquid water in snow, the absorption must be separable for the absorption due to solid water. The complex refractive indices (Warren 1984, Kou et al. 1994) were used to model the spectral properties of liquid water and ice, The complex refractive indices of these two phases of water are similar in overall magnitude and spectral trend. However, in detail these physical constants differ due to the different molecular bond energies of water in the liquid and solid state.

To investigate the contrast in spectral absorption between liquid water and ice, the transmittance of a 10 mm path through these materials was calculated (Figure 2). 'I'he spectral absorption are overlapping, but displaced in both the 1000 and 1200 nm spectral regions. The 1000 nm spectral region is selected for this research because snow is more reflective at these wavelengths and path lengths of 10 mm are expected in the snowpack (Dozier 1989).

3. AVIRIS MEASUREMENTS AND TRANSMITTANCE MODEL

AVIRIS measures the upwelling spectral radiance from 400 to 2500 nm at 10 nm intervals and collects images of 11 by up to 1000 km at 20 m spatial resolution. AVIRIS radi ante spectra acquired over Mammoth Mountain were inverted to apparent spectral reflectance (Green et al. 1990, 1993). An equivalent path transmittance model was developed for liquid water and ice in the 1000 nm spectral region. The model was inverted using a nonlinear least squares fitting routine to derive the equivalent path length transmittance of liquid water and ice for each spectrum measured by AVIRIS. A linear spectral albedo term is included in the model to compensate for illumination. For the AVIRIS spectrum in open snow below and adjacent to site A, the inverted spectral model returned values of 1.9 +- 0.1 mm liquid water and 13.3 +- 0.7 mm ice (Figure 3). The presence of liquid water due to surface melting at this elevation is consistent with the temperature time series prior to the AVIRIS acquisition. For site B to north of the summit of Mammoth Mountain the inverted model returned equivalent path transmittance of 0.0 mm liquid water and 20.1 +-0.9 mm (Figure 4). At the 3362 m summit, the temperature is calculated to be 2.6 degrees Celsius colder. Snow at these higher elevations and north facing slopes had not commenced surface melting at the time of AVIRIS data acquisition.

This equivalent path transmittance model was inverted for the entire AVIRIS scene of Mammoth Mountain (Figure 5). Absorption due to ice in snow at Mammoth Mountain and to the higher elevation in the northwest. At this late spring date, absorption due to ice was not measured at the lower elevations to the east and in the valley to the west of the mountain. The equivalent path transmittance duc liquid water was derived for the AVIRIS scene (Figure 6). Liquid water is measured in the AVIRIS spectrum in the snow at the lower elevations at Mammoth Mountain. As expected, liquid water is absent at the highest elevations of Mammoth Mountain where the snow is fully frozen. At low elevations, liquid water is also measured in the leaves of vegetation (Green et al., 1991). Liquid water in melting snow is spectrally distinguishable from liquid water in vegetation based either on the absorption of ice in snow or chlorophyll in vegetation.

4. CONCLUSION

Examination of the optical constants of liquid and solid water shows that in the 1000 run region these two phases of water are separable based upon their spectral properties. Measurement of these two phases of water requires spectral modeling of the overlapping absorption of the liquid water absorption centered at 970 nm and the ice absorption at 1030 nm. An equivalent path transmittance model was developed for liquid water and ice. This model was inverted using a non linear least squares spectral fitting approach for Mammoth Mountain AVIRIS data. Liquid water and ice were measured in melting snow below 2926 m based on spectral properties. Near the summit at 3362 m the only the absorption due to ice was measured. The occurrence of fully frozen snow at high elevation and melting snow at intermediate and low elevation is consistent with measured temperature and elevations at the time and date of the AVIRIS acquisition.

This first time remote measurement of the spectral absorption of liquid water in a melting snowpack will lead to new algorithms for the measurement, modeling and monitoring of snow driven hydrological processes.

5. FUTURE WORK

Future research will focus on development of a radiative transfer model of the snowpack when both the liquid and solid phase of water is present. In 1995 additional AVIRIS flights with in situ measurements will be used to further validate the measurement of these two phases of water in the snowpack.

6. ACKNOWLEDGMENTS

This research was carried out at the Jet Propulsion Laboratory, California Institute of technology, under contract with the National Aeronautics and Space Administration. Computational resources of the Center from Remote Sensing and Environment Optics (CRSEO), University of California, Santa Barbara, CA. were used.

7. REFERENCES

Dozier, J., "Remote Sensing of Snow in Visible and Near-Infrared Wavelengths," in Theory and Applications of Optical Remote Sensing, G. Asrar, cd., pp. 527-547, Wiley and Sons.

Green, R. O., 1990, "Radiative-transfer-barred retrieval of reflectance from calibrated radiance imagery measured by an imaging spectrometer for lithological mapping of the Clark Mountains, California," SPI E Vol. 1298, Imaging spectroscopy of the Terrestrial Environment.

Green, Robert O., James E. Conel, Jack S. Margolis, Carol J. Bruegge, and Gordon L. Hoover, 1991, "An Inversion Algorithm for Retrieval of Atmospheric and leaf Water Absorption From AVIRIS Radiance With Compensation for Atmospheric Scattering," Proc. Third AVIRIS Workshop, JPL Publication 91-28, pp. 51-61.

Green, R. O., J. E. Conel, D. A. Roberts, 1993, "Estimation of Aerosol Optical Depth, Pressure Elevation, Water Vapor and Calculation of Apparent Surface Reflectance from Radiance Measured by the Airborne Visible/lnframxl Imaging Spectrometer (AVIRIS) using a Radiative Transfer Code," SPIE, Vol. 1937, Imaging Spectrometry of the Terrestrial Environment, p. 2-11.

Kou-Lh, Labrie-D, Chylek-P, 1993, Refractive-hrdcxes Of Water And Ice In The 0.65 -Mu-M To 2.5-Mu-M Spectral, Range, J. Applied Optics, V. 32, N. 19, P. 3531-3540

Warren, S. G., "Optical properties of Snow," Reviews of Geophysics and Space Physics, vol. 20, pp. 67-89, 1982.

8. **FIGURES**

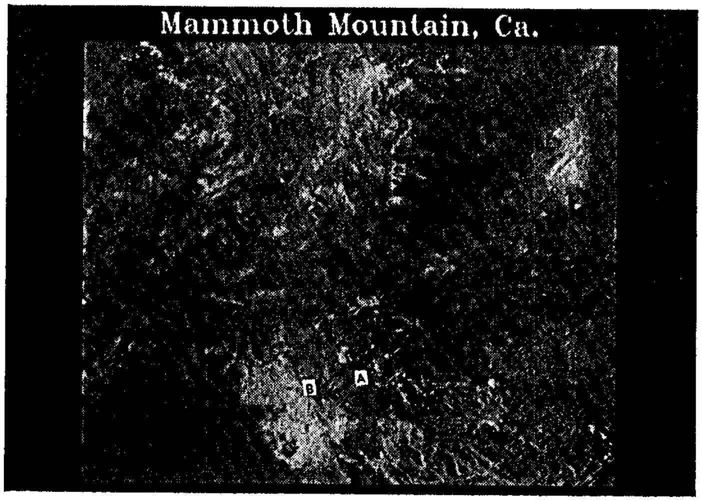

Figure 1. AWR1S image of Mammoth Mountain with ski runs in the lower center of the image. North is to the top. (See slide)

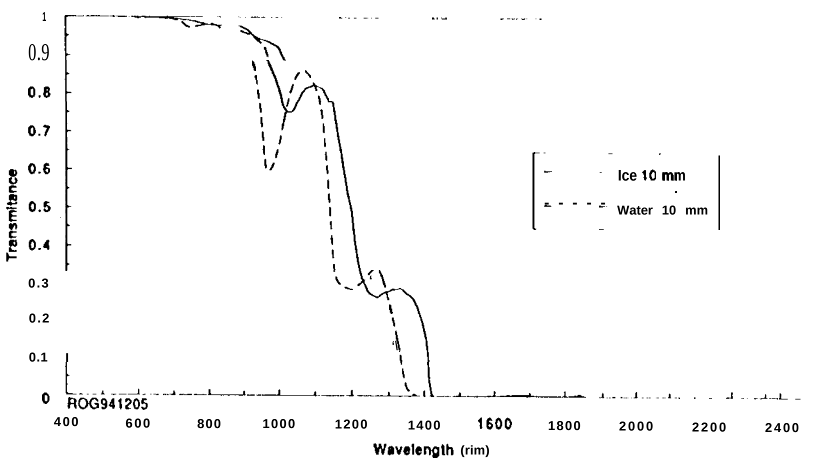

Figure 2. Transmission of light through 10 mm of water and ice.

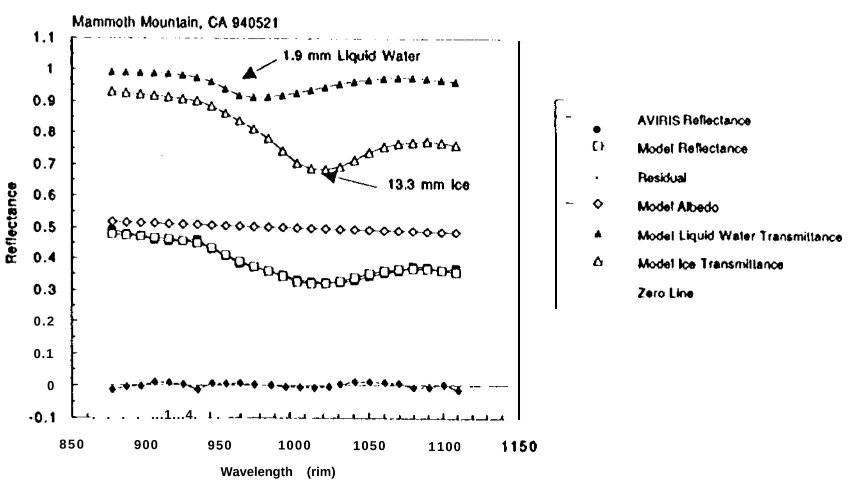

Figure 3. For silt A at Mammoth Mountain, CA, the AVIRIS measured spectrum and modeled spectrum when both liquid water and ice are present. Also shown is the residual disagreement and components of the model.

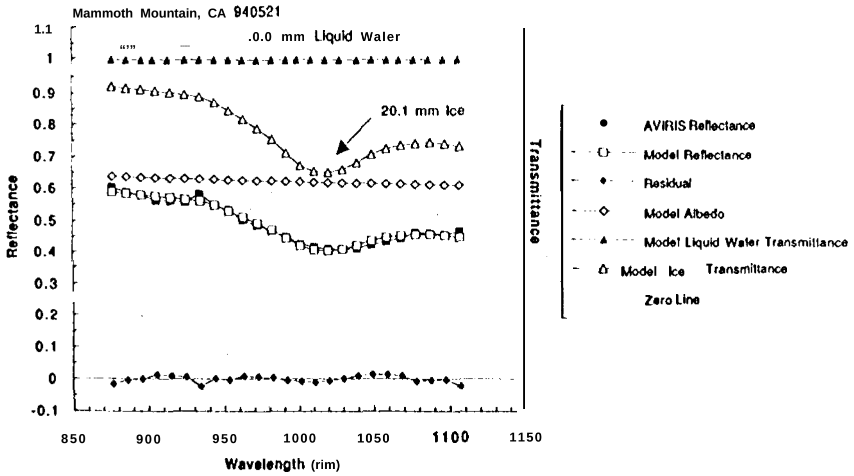

Figure 4. For site B, the AVIRIS measured spectrum and modeled spectrum when ice is present, but liquid water is absent.

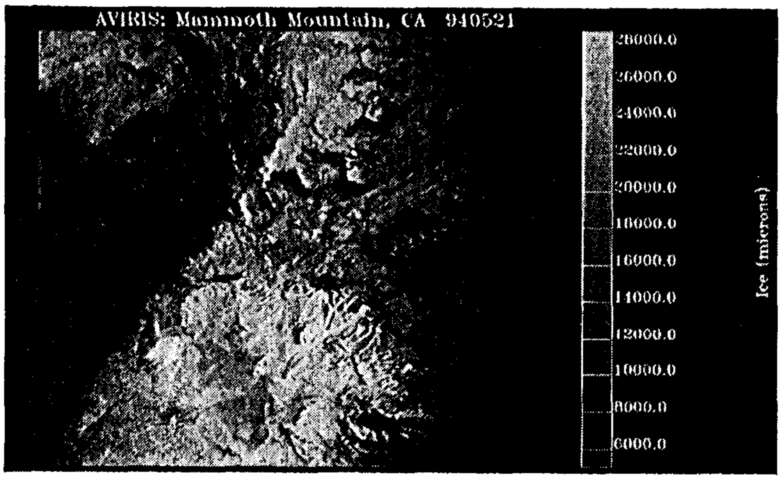

Figure 5. AVIRIS derived path equivalent transmittance image for ice at Mammoth Mountain, CA. Ice is present only on the higher elevation in the May data set. (See slide)

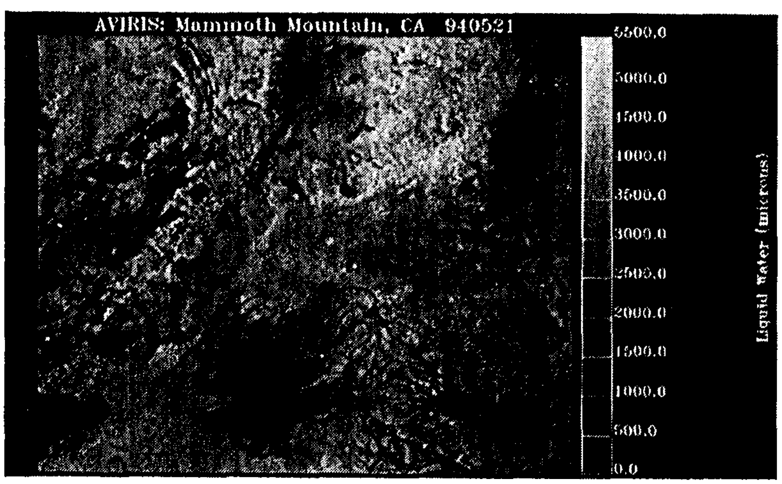

Figure 6. AVIRIS derived path equivalent transmittance image for liquid water at Mammoth Mountain, CA. Liquid water is present on the lower snow slopes of the mountain where the snow is melting. Liquid water is also measured in healthy vegetation. (See slide)